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# New Model Atmospheres: Testing the Solar Spectrum in the UV

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**Summary.** We present preliminary results on the calculation of synthetic spectra obtained with the stellar model atmospheres developed by Cardona, Crivellari, and Simonneau. These new models have been used as input within the SYNTHE series of codes developed by Kurucz. As a first step we have tested if SYNTHE is able to handle these models which go down to  $\log \tau_{\text{Ross}} = -13$ . We have successfully calculated a synthetic solar spectrum in the wavelength region 2000–4500 Å at high resolution ( $R = 522\,000$ ). Within this initial test we have found that layers at optical depths with  $\log \tau_{\text{Ross}} < -7$  significantly affect the mid-UV properties of a synthetic spectrum computed from a solar model. We anticipate that these new extended models will be a valuable tool for the analysis of UV stellar light arising from the outermost layers of the atmospheres.

## 1 Introduction

A set of spectral energy distributions (SEDs) is a very useful tool to analyze stellar spectra and the integrated spectral properties of stellar systems (via some evolutionary population synthesis code, see e.g. Buzzoni 1995). Observational atlases of stellar SEDs generally lack of homogeneous and complete coverage of the main stellar parameters ( $T_{\text{eff}}$ ,  $\log g$  and  $[M/H]$ ), therefore many of the recent population analyses rely on results of stellar atmosphere modelling, a practise that has been eased with the development of faster computers and sophisticated computational codes. In order to calculate a theoretical stellar SED it is necessary to have a model atmosphere which describes the physical quantities at different depths and, ideally, a complete set of opacities that account for the absorption of the radiation passing throughout the atmosphere.

During the last decades several groups have developed computational codes capable to calculate model atmospheres and spectra at high resolution, some of whom have allowed the public use of their codes, among others, the codes ATLAS9, ATLAS12 and SYNTHE built by Kurucz<sup>4</sup> (1993a,b) and TLUSTY and SYNSPEC constructed by Hubeny & Lanz<sup>5</sup> (1992). In particular, ATLAS9 and SYNTHE codes have been used by our group to calculate the UVBLUE grid of theoretical SEDs and to investigate its potential for stellar and populations studies in the ultraviolet (UV) wavelength interval (see Rodriguez-Merino et al. 2005 for more details).

The UV wavelength range has historically been challenging in many branches of modern astrophysics since the observed stellar spectra are not well reproduced by predictions of theoretical models. One possible reason is the missing opacity problem (see Holweger 1970; Gustafsson et al. 1975), but another probable reason is actually that most of the model atmospheres do not provide the atmosphere structure near the stellar surface, where most of the UV radiation emerges. Therefore, it is crucial to calculate new models which describe the outermost layers of the stellar atmospheres.

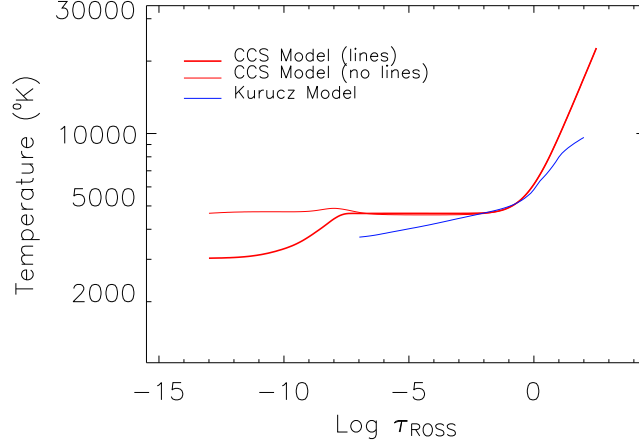
In this work we briefly describe the structure of a new model atmosphere for the Sun which incorporates layers down to  $\log \tau_{\text{Ross}} = -13$ . That is, optical depths more than five orders of magnitude thinner compared to classical models currently in use. This model has been coupled to SYNTHE codes for testing their compatibility and exploring the effects of such layers on the UV flux.

## 2 Model Atmospheres

The model atmospheres employed here have been developed by Cardona, Crivellari and Simonneau (CCS), these models use the Implicit Integral Method to solve the radiative transfer (Crivellari & Simonneau 1994; Simonneau & Crivellari 1993; Crivellari et al. 2002); this algorithm allows a stable and precise computation down to very low values of  $\tau_{\text{Ross}}$ . The models are based on approximations typical of classical models, namely, plane-parallel and homogeneous layers, steady state, hydrostatic, local thermodynamical, and radiative equilibria (convection has not been included here). We have considered the continuum opacity of ten elements (H, He, C, N, O, Na, Mg, Al, Si, Ca) and for three of them also the line opacity accounting for 20 absorption lines (12 for H, 6 for He, and 2 for Ca), which provide the large part of the absorption needed to compute the atmospheric structure. Figure 1 displays a comparison between the temperature profile of the new model atmosphere with and without line opacity (*solid thick* and *thin lines*, respectively) and a Kurucz's model (*dotted line*) with similar physical parameters ( $T_{\text{eff}} = 5780$  K,  $\log g = 4.5$ ,  $[\text{M}/\text{H}] = +0.0$ ).

<sup>4</sup> <http://kurucz.harvard.edu/>

<sup>5</sup> <http://nova.astro.umd.edu/>

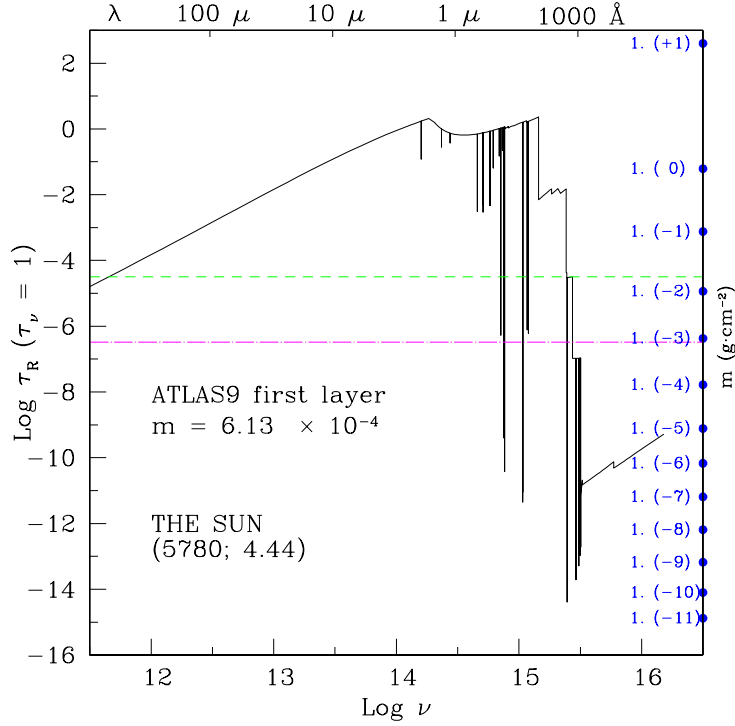


**Fig. 1.** The temperature profile of the CCS model atmosphere, with (*thick curve*) and without (*thin curve*) line opacity, and of a Kurucz model (*dotted curve*) for solar physical parameters.

In order to explore qualitatively the role of the most external atmospheric layers, in Fig. 2 (kindly provided by L. Crivellari) we track the value of the Rosseland optical depth at which the atmosphere becomes optically thin at each frequency. We can see how several strong lines and, in particular, the Lyman lines and break, which dominate the UV range, are produced in the most external layers ( $\log \tau_{\text{Ross}} \sim -7$  to  $\log \tau_{\text{Ross}} \sim -13$ ). Currently, there are no classical model atmospheres that take into account the effects of these external regions in the SEDs of stellar models.

### 3 Synthetic Spectra

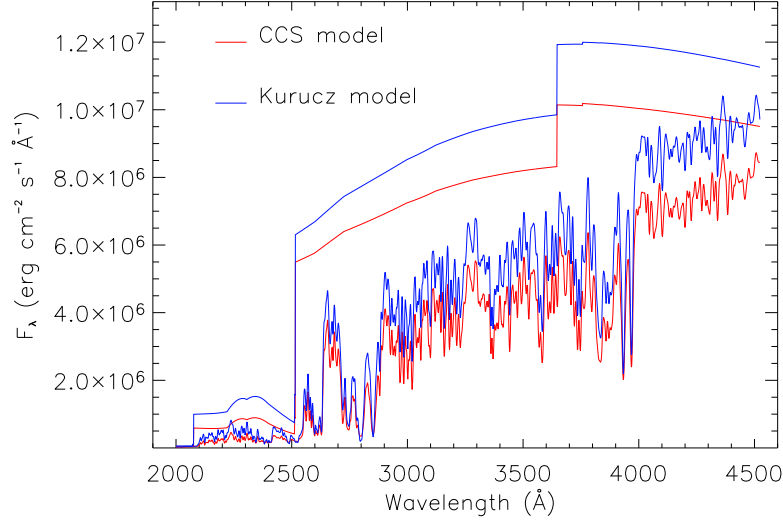
Once a model atmosphere has been computed the next step is to calculate the synthetic spectrum by solving the transfer equation at every layer in the atmosphere. Since the model here presented was not calculated within the Kurucz machinery, our main goal was to test if SYNTHE is able to handle extended models, and if so, run SYNTHE with the new model and analyze the effects of the layers at depths in the interval  $\log \tau_{\text{Ross}} \sim -7 - \log \tau_{\text{Ross}} \sim -13$  on the emergent spectrum. After successfully modifying the output of the solar CCS model with line opacity to be compatible with the input data required by SYNTHE, we computed a synthetic spectrum at high resolution ( $R = \lambda/\Delta\lambda = 522\,000$ ) covering the near ultraviolet interval, from 2000 to 4500 Å. The line list by Kurucz (1992) has been adopted to account for individual line absorption. In Figure 3 we display the spectra (pure continuum and



**Fig. 2.** Rosseland optical depth of formation of the main absorption features in a solar model as a function of frequency. The dot-dashed line displays the upper layer of the Kurucz model. Note that the UV features form well above the limiting  $\log \tau_{\text{ROSS}} \sim -7$ .

continuum + line absorption) obtained with CCS model (*solid line*) and a Kurucz’s solar model (*dotted line*). For the sake of clarity, line spectra have been degraded with a Gaussian kernel to a resolution of  $\text{FWHM}=6 \text{ \AA}$ . Although we are well aware that at present it is not possible to carry out any detailed comparison between the calculated SED of the new model with either results from other codes or observed data (mainly due to the lack of line opacity and convective transport), it is interesting to note that the CCS model fluxes are systematically lower in the wavelength interval employed.

Another interesting exercise we have conducted is the comparison of the effects on the UV-blue spectrum of different parts of the atmosphere. We have segmented the CCS model so as to have three models with different limiting optical depth at the surface:  $\log \tau_{\text{ROSS}} = -13$ ,  $\log \tau_{\text{ROSS}} = -10$ , and  $\log \tau_{\text{ROSS}} = -7$ . For each model we have calculated a synthetic spectrum (at  $R = 522\,000$ ). Figure 4 shows the flux ratios in two spectral windows, 2000–2550  $\text{\AA}$  (*left panels*) and 4000–4550  $\text{\AA}$  (*right panels*), using the flux of the

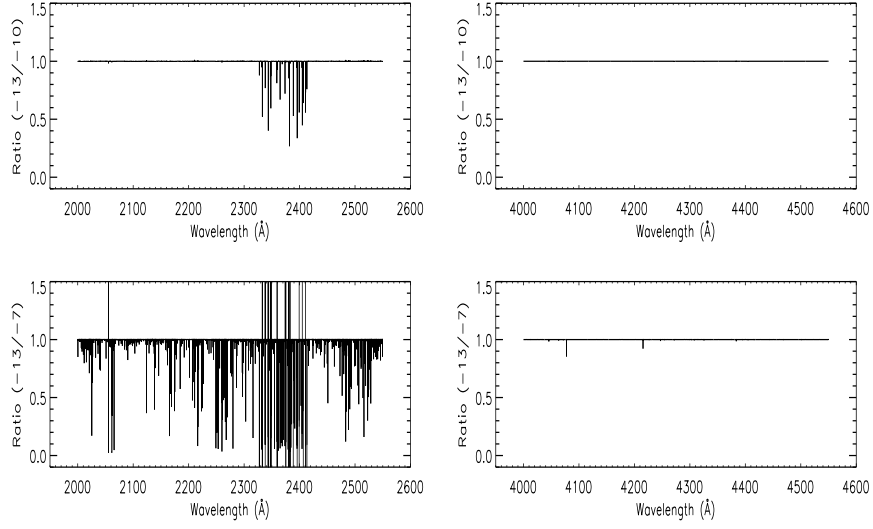


**Fig. 3.** Near-UV synthetic solar spectra computed with SYNTHE using the CCS model with line opacity and Kurucz model atmospheres. Spectra are shown at a resolution of FWHM=6 Å.

model with limiting depth  $\log \tau_{\text{Ross}} = -13$  as a reference. In the lower left panel, where we plot the ratio  $F_{\lambda}(\log \tau_{\text{Ross}} = -13)/F_{\lambda}(\log \tau_{\text{Ross}} = -7)$ , we can visualize the strong effects of the external layers, which produce deeper lines. These effects might turn out to be important also in models which include non-thermal heating.

## 4 Concluding Remarks

The main result of this work is that SYNTHE series of codes is capable of treating the CCS model atmospheres, which reach very low values of  $\tau_{\text{Ross}}$ . The analysis of the effects of extending the atmosphere indicates that at mid-UV wavelengths the effects are significant while negligible in the blue. The following steps are to extend the analysis to models with atmospheric parameters different of the Sun, to complement the opacity (both continuous and of lines) as well as to introduce more chemical species. We are in the process of including convection for intermediate and cool star models. A detailed comparison at high resolution with an observed solar atlas (Kurucz et al. 1984) is also underway.



**Fig. 4.** Flux ratio of synthetic spectra computed from models with different  $\tau_{\text{Ross}}$  limits (see Sec. 3 for explanation).

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